



oceanographic cruise to the bering and chukchi seas,  
summer 1949

PART IV: PHYSICAL OCEANOGRAPHIC STUDIES: VOL. 1. DESCRIPTIVE REPORT

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## statement of problem

Investigate problems in oceanography through suitably devised methods, means, and equipments. This report presents the results of physical oceanographic measurements made in the shallow eastern Bering and Chukchi Seas.

## conclusions

1. The oceanographic structure—temperature and salinity—of the region exhibits pronounced layering with each layer nearly uniform vertically. The temperature-salinity relations were consistent allowing a classification of the water masses, or layers, thus making it possible to follow the geographical continuity of the water.
2. The annual development of the water masses can be accounted for by (a) the cooling effect of winter conditions and the freezing of the ice, (b) melting of the ice in spring and summer, (c) drainage and run-off from the continental areas, (d) modification by heating, and (e) modification by mechanical mixing.
3. Water masses found in both the eastern Bering and Chukchi Seas are: (a) *Deep Shelf Water*: uniform cold high-salinity water derived from winter conditions and lying along the bottom in the deeper regions of the Bering and Chukchi Sea shelves, but not present in the Bering Strait in late summer; (b) *Modified Shelf Water*: Deep Shelf Water which has retained its high salinity, but since it is near the surface has been heated several degrees; (c) *Alaskan Coastal Water*: warm water along the coast with greatly varying salinities caused by fresh water drainage from the west coast of Alaska; and (d) *Intermediate Water*: a wedge of water lying between, and probably formed by mixing between, Modified Shelf Water and Alaskan Coastal Water.

Additional water masses observed in the Chukchi Sea are: (a) *Siberian Coastal Water*: a counterpart to the Alaskan Coastal Water but lower in temperature, resulting from drainage on the north coast of Siberia; (b) *Ice Melt*: low-salinity water at the surface in the immediate vicinity of and in temperature equilibrium with the melting ice; and (c) *Modified Ice Melt*: surface water fringing the Ice Melt and having similar salinities but modified by heating.

4. Summer currents in the eastern Bering Sea move slowly northward, increasing in speed at Bering Strait due to the geographical constriction. Superimposed on this slow drift is a faster northward coastal current confined primarily to the Alaskan Coastal Water. The Siberian Coastal Current, the Alaskan Coastal Current, and the westward drift along the southern margin of the ice pack combine to establish a broad counter-clockwise circulation in the Chukchi Sea.

## recommendations

1. Obtain observational data at other seasons of the year to establish conclusively the annual cycle of oceanographic structure and currents.
2. Undertake a limited study of the region between Cape Lisburne and Pt. Barrow to tie together the Bering and Chukchi Sea investigations with those in the Arctic and Beaufort Seas.

## work summary

During the two-month cruise in the summer of 1949, systematic measurements were made during a survey from the vicinity of St. Lawrence Island to Bering Strait, several surveys in Bering Strait, two surveys northward from the Strait, and the return survey from Bering Strait to Unimak Pass. The temperature, salinity, and density of the water were established, and the distribution, movements, and interaction of the water masses investigated.

The scientific group aboard HMCS CEDARWOOD was made up of J. P. Tully, A. J. Dodimead, and R. H. Herlinveaux of the Pacific Oceanographic Group of Canada, and E. C. LaFond, R. M. Lesser, J. C. Roque, and J. F. T. Saur, of the U. S. Navy Electronics Laboratory. F. G. Barber and G. L. Pickard of University of British Columbia, though primarily participating in the shore station program at Wales, assisted with observations while on board.

## preface

During the months of July and August, 1949, the U. S. Navy Electronics Laboratory and the Canadian Pacific Oceanographic Group collaborated in a varied program of acoustical and oceanographic research, mainly in the Bering and Chukchi Seas. This joint venture was made possible through the cooperation of agencies of the Canadian and United States Navies who furnished the vessels and necessary funds for the cruise.

Oceanographic measurements aboard the United States vessels were taken primarily for the valuation of experimental sound-transmission and sound-propagation data. The collection of sound data took priority, and oceanographic data could be collected only when no interference with sound experiments was assured. The time of the Canadian vessel was devoted exclusively to oceanography, and the data collected by this ship are intended to supplement our present knowledge of the physical and chemical characteristics of Arctic waters.

The expedition was made by three ships which formed a small task group under the military command of Commander John D. Mason, USN. Dr. Waldo K. Lyon of the Navy Electronics Laboratory directed the entire acoustic and oceanographic program, with Dr. J. P. Tully of the Pacific Oceanographic Group as senior scientist in charge of the Canadian Group.

Participating ships were:

USS BAYA (AG(SS) 318), under the command of CDR John D. Mason, USN;  
HMCS CEDARWOOD, under the command of LCDR J. E. Wolfenden, RCN(R);  
USS EPCE(R) 857,\* under the command of LCDR D. J. McMillan, USN.

The oceanographic program was divided into three major parts:

1. *Physical oceanographic studies.* These were carried on primarily aboard HMCS CEDARWOOD and from a shore station at Cape Prince of Wales. Some supplemental data were collected aboard USS EPCE(R) 857 and USS BAYA.

2. *Oceanographic measurements as adjuncts to, and in support of, sonar work.* These measurements were taken from USS BAYA and USS EPCE(R) 857.

3. *Sea floor and biological studies.* This work was primarily conducted aboard USS EPCE(R) 857, with some additional work on HMCS CEDARWOOD.

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\* Now designated USS PCER 857.

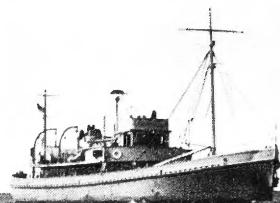
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## introduction

This report, the fourth of the series on the cruise, is concerned with the physical oceanographic studies conducted in the shallow waters of the eastern Bering and Chukchi Seas.\* Results of the studies of the sea floor and currents, and oceanographic investigations in the deep Bering Sea are covered in separate reports.<sup>1,2,3</sup>

The dearth of oceanographic information in the Chukchi Sea and of coordinated observations of the water structure to any distance on either side of the Bering Strait has been brought out in previous reports. The program, therefore, was designed to determine in more detail than had previously been accomplished the vertical and horizontal temperature and salinity structure of the water in the approaches to Bering Strait and especially in the Chukchi Sea region north of the Strait. The temperature, salinity, and density of the water were to be established, and the distribution, movements, and interaction of the water masses were to be investigated.

The objectives were obtained by a survey from the vicinity of St. Lawrence Island to Bering Strait, several surveys in Bering Strait, two surveys northward from the Strait, and the return survey from Bering Strait to Unimak Pass. Because of time and operational considerations, the ice was reached on only one occasion for a period of 8 hours so that the coverage north of 70°N latitude, especially in the region near the ice, was not as complete as desired. The operation provided good data in the areas covered and valuable experience on oceanographic operations in the Arctic regions.

## previous investigations

The complicated physical oceanography of the Bering and Chukchi Seas has been investigated by various organizations. The Norwegian ship *Maud* obtained considerable oceanographic data in the western Chukchi Sea between Herald Shoal and Wrangel Island, but occupied only two serial stations east of 170° W.<sup>4</sup>

Other principal pre-World War II investigations were carried out by University of Washington oceanographers in the summers of 1934, 1937, and 1938 aboard U. S. Coast Guard vessels.<sup>5,6</sup> On these cruises, comprehensive chemical and physical oceanographic data were obtained at serial stations giving wide coverage in the eastern Bering Sea and Bering Strait, and on one occasion data were obtained along the Alaskan Coast nearly to Pt. Barrow. Recent translations of Russian documents<sup>7</sup> furnish

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\*Volume 2 of this report contains the observational data.

<sup>1</sup> E. C. Buffington, et al. *Oceanographic Cruise to the Bering and Chukchi Seas, Summer 1949, Part I: Sea Floor Studies* (Navy Electronics Laboratory, Report 204) 2 October 1950.

<sup>2</sup> R. M. Lesser and G. L. Pickard *Oceanographic Cruise to the Bering and Chukchi Seas, Summer 1949, Part II: Currents* (Navy Electronics Laboratory, Report 211) 24 October 1950 (CONFIDENTIAL)

<sup>3</sup> J. F. T. Saur, et al. *Oceanographic Cruise to the Bering and Chukchi Seas, Summer 1949, Part III: Physical Observations and Sound Velocity in the Deep Bering Sea* (Navy Electronics Laboratory, Report 298) 6 June 1952 (CONFIDENTIAL)

<sup>4</sup> H. U. Sverdrup "The Waters on the North-Siberian Shelf" (In: *The Norwegian North Polar Expedition with the "Maud," 1918-1925 Scientific Results*) J. Griegs, vol. 4, no. 2, 1929, pp. 34-40.

<sup>5</sup> C. A. Barnes and T. G. Thompson *Physical and Chemical Investigations in Bering Sea and Portions of the North Pacific Ocean* University of Washington, 1938.

<sup>6</sup> J. R. Goodman, et al. *Physical and Chemical Investigations: Bering Sea, Bering Strait, Chukchi Sea, during the Summers of 1937 and 1938* University of Washington, 1942.

<sup>7</sup> G. E. Ratmanoff *Explorations of the Seas of Russia* (Hydrological Institute, Leningrad, Publication no. 25) 1937, pp. 1-175.

additional chemical and physical data on the western Bering Sea and Bering Strait, and some data are given in a Japanese publication<sup>8</sup> concerned primarily with the oceanography along the Asiatic Coast.

During World War II, the U. S. Navy collected large numbers of bathythermograms in the southern Bering Sea. These data provide detailed temperature structures of the upper layers,<sup>9</sup> but no concurrent salinity data are available.

Post-war investigations consist of bathythermograph sections and a few serial stations obtained in 1946, 1948,<sup>10</sup> and 1950<sup>11</sup> from icebreakers on runs through the Bering and Chukchi Seas to Point Barrow. These observations were made by personnel of the U. S. Coast Guard, U. S. Hydrographic Office, University of Washington, and Scripps Institution of Oceanography. The Fish and Wildlife Service obtained surface and bottom temperature data in eastern Bering Sea in June and July 1949,<sup>12</sup> the same year as the cruise reported here. In the summer of 1947 complete oceanographic stations were occupied through the Bering and Chukchi Seas to a latitude of 72°N by personnel from the Navy Electronics Laboratory and the Scripps Institution of Oceanography aboard the USS NEREUS.<sup>13</sup> The majority of these data were taken in the central and eastern Chukchi Sea and comprise the major work in this region north of Bering Strait previous to the presently reported cruise.

## observations

HMCS CEDARWOOD occupied 192 serial stations, the locations of which are shown in figure 1. During the first part of the cruise, in the southern area, a bathythermograph and a C-T-D (conductivity-temperature-depth) instrument were used at each station and a Nansen-bottle cast was made at about every fifth station. The use of the C-T-D, which recorded the three variables simultaneously as the element was lowered into the water, was discontinued because too great inaccuracies in conductivity were caused by the slow rate of flushing of the cell. Reversing thermometers were removed from the water sampling bottles after station 44 for two reasons, (1) a delay in time was required for the thermometers to reach equilibrium, and (2) because of the magnitude of short-period fluctuations and the ranges encountered, an accuracy of better than  $\pm 0.2^{\circ}\text{F}$  (which could be obtained with a bathythermograph) was not considered necessary.

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<sup>8</sup> K. Hidaka *Oceanographic Investigations in the West Pacific Ocean, Part I: The Northern Area of the West Pacific Ocean*, No. 1. Investigations from the Standpoint of Marine Physics (Eastern Asia Research Institute) 1952.

<sup>9</sup> J. G. Pattullo, et al. *Sea Temperature in the Aleutian Island Area* (Scripps Institution of Oceanography, Oceanographic Report no. 24) April 1950.

<sup>10</sup> C. W. Thomas *Physical and Zoological Investigations in Bering Sea and Portions of the Arctic Ocean* (Coast Guard) 1948 (CONFIDENTIAL).

<sup>11</sup> U. S. S. BURTON ISLAND (AGB-1) *Beaufort Sea Oceanographic Expedition, Summer 1950* August 1950 (CONFIDENTIAL).

<sup>12</sup> J. G. Ellson, et al. *Exploratory Fishing Expedition to the Northern Bering Sea in June and July, 1949* (Fish and Wildlife Service, Fishery Leaflet no. 369) March 1950.

<sup>13</sup> E. C. LaFond, et al. *Oceanographic Measurements from the USS NEREUS on a Cruise to the Bering and Chukchi Seas, 1947; interim report* (Navy Electronics Laboratory, Report 91) 25 February 1949.

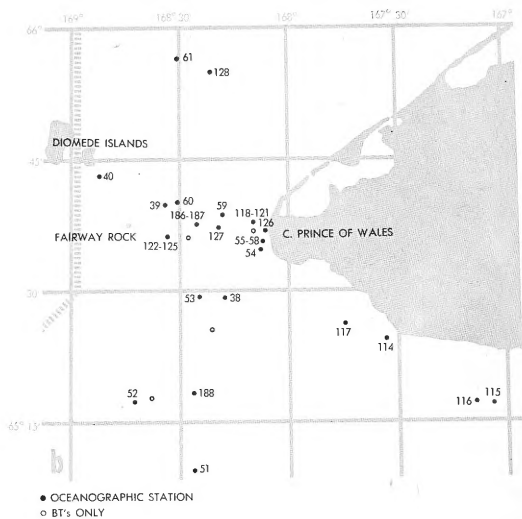
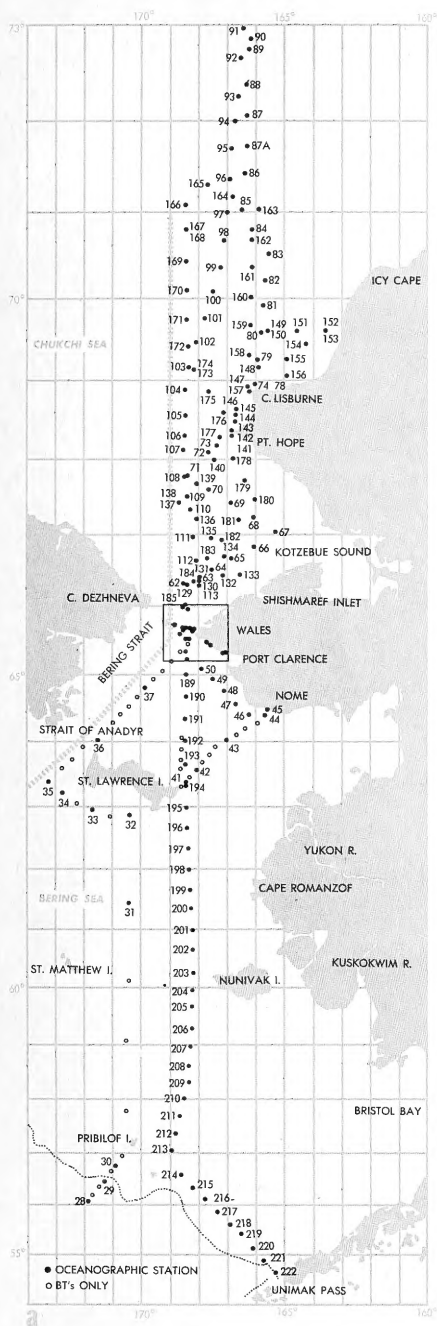


Figure 1. Location of stations, summer 1949: (a) eastern Bering and eastern Chukchi Seas; (b) Bering Strait.

Thereafter, a standard procedure was adopted for all stations. When the ship had stopped, a bathythermograph was first lowered to the bottom. The slide thus obtained was placed with its grid in a photographic enlarger and projected to show the thermal structure. From this trace, the depths of water sampling were selected. They usually included at least the surface, a depth just above the thermocline, one below the thermocline, and one near the bottom. The number of samples taken depended upon the complexity of the thermal structure and the depth to the bottom, but usually ranged from five to seven.

Nansen bottles without attached thermometers were placed appropriately on the line to take water samples at the selected depths. A record of the temperature was obtained from the bathythermograph secured to the end of the same line. The complete operation took about 15 minutes and was repeated about every two hours if the ship remained at the same location.

A single 180-foot-maximum-depth (Bristol 20120) bathythermograph was used for 554 lowerings and a 450-foot instrument was used for 27 lowerings in the area of the southeastern Bering Sea. Additional observations (such as plankton-net hauls, bottom samples, surface-current and bottom-current measurements) were made at selected stations and have been reported separately.<sup>1,14</sup>

Salinity analyses and preliminary analysis of bathythermograms were performed aboard ship for several reasons. They made it possible to evaluate and modify the over-all program in the field, to determine and obtain the most pertinent information in the time available, to determine the proper operation of gear, and to avoid accumulation of water samples.

The BT slides were placed in a grid, adjusted for preliminary temperature corrections, and projected and traced on mimeographed grid prints which had been prepared in advance. The water samples were titrated on shipboard and the salinity calculated to an accuracy of  $\pm 0.05$  ‰. The salinity was then plotted on the grid with the temperature trace. Density values ( $\sigma_t$ ) were calculated by means of a nomogram and also plotted on the grid. From these vertical traces preliminary geographic sections of temperature, salinity, and density were prepared. This procedure of shipboard preliminary processing proved to be highly satisfactory.

Detailed processing and analysis were carried out ashore. The serial data are tabulated and horizontal and vertical sections of temperature, salinity, and density distributions are given in volume 2 of this report.

## geography

The eastern Bering and Chukchi Seas lie on the broad continental shelf of Alaska. The continental shelf is remarkably flat, varies in depth primarily between 20 and 30 fathoms, and has a mud and sand bottom shoaling gradually and regularly toward the coastline. Detailed descriptions of the topography and sediments of the region are given in the first report of this series<sup>1</sup> and a report of the NEREUS cruise in 1947.<sup>13</sup>

The shallow coastal seawater system is bounded on the southwest and south by the deep Bering Sea and the Aleutian Islands, on the east by the coast of Alaska, on the west by Siberia, and on the north by the Arctic Ocean. The system is divided into two distinct regions by the Bering Strait which separates the Bering Sea from the Chukchi Sea. Oceanic water is supplied to the southern part of the system by the flow northward through the eastern Aleutian Islands and perhaps also by a weak northeastward flow

<sup>14</sup> Navy Electronics Laboratory, Report 148 *Oceanographic Cruise to the Bering and Chukchi Seas, Summer 1949; Interim Summary Report 19 October 1949 (CONFIDENTIAL)*.

across the deep Bering Sea.<sup>3,6</sup> Fresh water is contributed to the eastern Bering Sea by two large Alaskan rivers, the Kuskokwin and the Yukon. A third large river, the Anadyr in Siberia, also empties into the general region but its effects are felt southwestward along the Siberian coast. In the Chukchi Sea region three rivers flowing into Kotzebue Sound also contribute a large amount of fresh water. Additional details of the geography are brought out in the excellent descriptions of the area by Barnes and Thompson<sup>5</sup> and by Goodman, Lincoln, Thompson, and Zeusler.<sup>6</sup>

## water structure

### GENERAL CHARACTER

Vertical distributions of temperature and salinity in nearly the whole region exhibited a pronounced layering effect typical of coastal systems involving large quantities of run-off. Relatively sharp boundaries separated these layers which in themselves could be considered virtually uniform with depth (fig. 2). Frequently in horizontal distributions, distinct boundaries also separate water of different characteristics. These geographic distributions will be discussed after first establishing the characteristics of the water masses in the region.

The temperature-salinity (T-S) relation (correlation of temperature with salinity) was investigated to determine if it could be used to identify the water masses of the region. This procedure has been used frequently in oceanic studies to classify and identify water masses and to trace their movement. It has been used less frequently in coastal or shallow water studies because of the effect of changes at the atmospheric and the coastal boundaries. The temperature and corresponding salinity of each water sample is plotted on a graph using temperature as the ordinate and salinity as the abscissa, as shown for selected stations in figure 8.\* These points with the depth indicated are joined by a smooth curve. If the relation is consistent between various stations in shape and location on the diagram, the curve for any individual station can then be used to identify the water mass or masses present.

The T-S relations in the Bering and Chukchi Seas were consistent. Such consistency in this shallow-water region was maintained because the surface boundary effect was minimized by a constant stratus overcast and high relative humidity during this time of year. At any given station, except those close to the coast, the points for depths above the thermocline were closely grouped, as were those for depths below the thermocline (fig. 8). A wider scatter of points occurs as a result of geographic variation when the points for all the stations are plotted (fig. 2a). Nevertheless, a general grouping of points occurs so that water masses can be identified and the geographic continuity of a given water mass can be followed.

The water masses used here should not be confused with the deep-sea water-mass classifications of Helland-Hansen<sup>15</sup> and Sverdrup.<sup>16</sup> The water masses defined here are purely local and apply only to the shallow Bering and Chukchi Seas and are used as tools to trace the continuity and development of the system. Certain of these masses may be only transient and not even in existence throughout the whole year. They also may vary somewhat from year to year, but the general structure of the system as indicated by these water masses appears consistent with previous data.<sup>5,6,7,8,13</sup>

\* Figures 8 through 13 appear as foldouts at the end of the report.

<sup>15</sup> B. Helland-Hansen "Nøgen Hydrografiske Metoder" *Skandinaviske Naturforsker Møte* 1916.

<sup>16</sup> H. U. Sverdrup, et al. *The Oceans, Their Physics, Chemistry, and General Biology* Prentice-Hall, 1942.

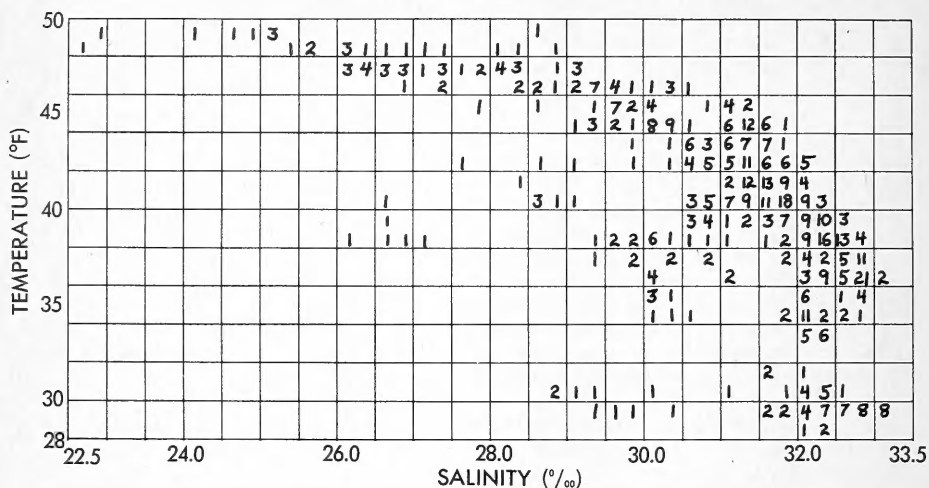


Figure 2a. Frequency of T-S relationships in the Chukchi Sea from interpolated depths of 0, 20, 40, 60, 80, 100, 125, 150 feet. Figures show number of observations in unit of diagram 1°F by 0.25‰ salinity.

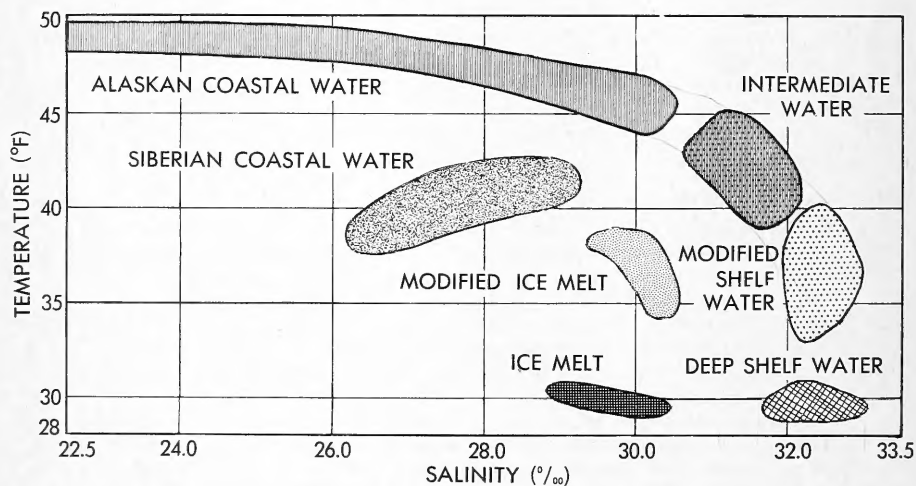


Figure 2b. T-S relationships used to designate water masses of the eastern Bering and Chukchi Seas.

Figure 2a shows the frequency scatter diagram for the samples at given depths at all of the stations occupied in the Chukchi Sea. In the upper part of the diagram, a relationship exists in which the salinity changes over a wide range from around 20 ‰ to 30 ‰ while the temperature varies only between 50° and 46°F. This grouping of points identifies the surface water near the coast of Alaska and will be called Alaskan Coastal Water (ACW) (fig. 2b).

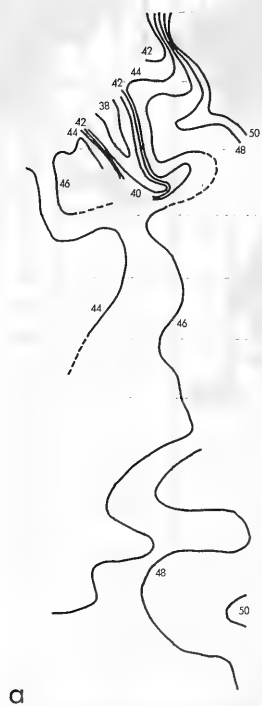
Around 45°F and 30.5 ‰, the slope of the relationship changes and remains constant to about 40°F and 32.0 ‰. Observed values which cluster about the line joining these points are characteristic of a second water mass designated as Intermediate Water (IW). A further grouping occurs in the region approximately bounded by 34° to 40°F and 32.00 to 33.00 ‰. This relationship is typical of the water lying on the bottom throughout most of the area during late summer and will be labeled Modified Shelf Water (MSW). The water mass defined by the group of observed values around 30°F and between 31.50 and 33.00 ‰ will be designated as Deep Shelf Water (DSW). The above four water masses include the majority of the observations and are applicable also to the T-S relation found in the northern part of the eastern Bering Sea. Southward from St. Matthew and Nunivak Islands the slightly higher salinities, about 31.0 to 32.0 ‰, obtained in the warm surface water, 46° to 50°F, were due to the influence of surface water from the Pacific filtering through the passes of the eastern Aleutian Islands.

In the Chukchi Sea three additional water masses are present. Fewer points for these masses are shown in figure 2a as each covered only a small geographic area and was thus sampled less often. One of them exhibits a wide range of low salinity, 26 to 29.5 ‰, similar to the Alaskan Coastal Water but with lower temperatures, 38° to 43°F. This is Siberian Coastal Water (SCW) originating north of Bering Strait. Siberian Coastal Water from south of Bering Strait was not encountered. The water mass having a temperature of near 30°F and salinity between 28.75 and 30.50 ‰ is found only in the region of the melting ice and is called Ice Melt (IM). The last water mass occurs in the diagram (fig. 2a) around 38°F and 30 ‰. It is a surface water mass separating the Ice Melt and the Intermediate Water and will be designated Modified Ice Melt (MIM).

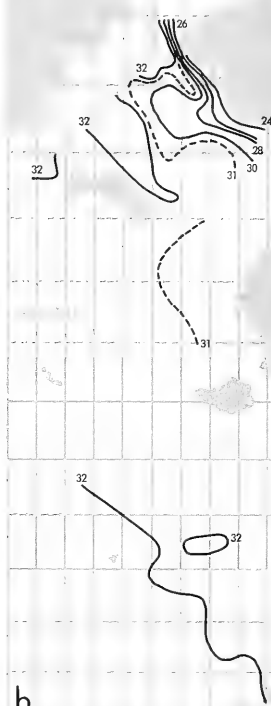
The above designations are made for convenience in the following discussion of the distribution of the water masses in the eastern Bering Sea, Bering Strait, and eastern Chukchi Sea.

## EASTERN BERING SEA

Temperature and salinity distributions at the surface in the eastern Bering Sea from the present data are shown in figure 3. These should be considered as "smoothed" representations for the period of the survey, as definite fluctuations and development of the distributions with time were observed, particularly just to the north of St. Lawrence Island. In figure 4, similar representations are shown for a depth of 80 feet (approximately 25 meters). The close relation between the temperature and salinity distributions in the eastern Bering Sea is very striking. In general, warm low-salinity water lies close to the coast grading to cold high-salinity water at a distance from the coastline, both at the surface and at depths. Alaskan Coastal Water lies close to the shore and has the highest temperatures and lowest salinities observed in this region. The Modified Shelf Water appears farther from the coast and just northward from St. Lawrence Island as an area of cold high-salinity water widening to the northwest. Due to the time differences and spacing of the lines of observation, the data could be interpreted in two ways, that shown in figures 3 and 4 is believed representative of conditions in July and early



a



b

Figure 3. Distributions of (a) surface temperature ( $^{\circ}\text{F}$ ) and (b) surface salinity ( $\text{‰}$ ) in the eastern Bering Sea.

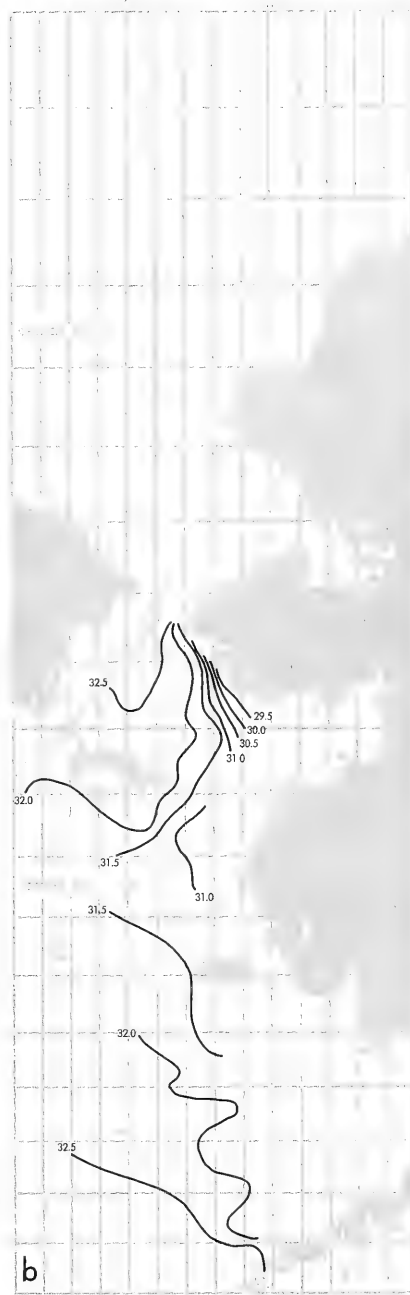
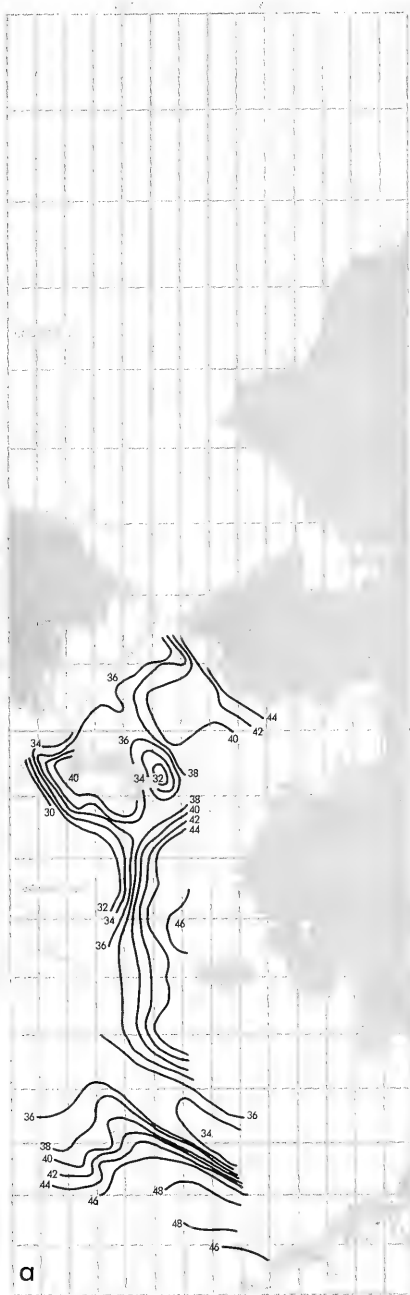


Figure 4. Distributions of (a) temperature ( $^{\circ}\text{F}$ ) and (b) salinity ( $\text{‰}$ ) at 80 feet in the eastern Bering Sea.

August. The other interpretation would be representative of mid-August when the flow of warmer water around the west tip of St. Lawrence Island and westward from the north side of Norton Sound leaves an isolated cold spot to the north of the east tip of St. Lawrence Island. This situation is shown in the analysis by Hidaka<sup>8</sup> and the late-summer data of University of Washington,<sup>5,6</sup> and can be seen occurring at the 80-foot level in our data. Further observations in this region are required to determine the details of the development.

The Intermediate Water separates the Alaskan Coastal Water and the Modified Shelf Water. The Intermediate Water appears to originate in the region of Nunivak Island and Cape Romanzof where the water is almost homogeneous from top to bottom. The mechanism which brings about the pronounced uniformity is not definitely known at the present. To the north of this region the Intermediate Water is maintained as a transitional zone between the Alaskan Coastal Water and the Modified Shelf Water. It nevertheless exhibits boundaries in the vertical profile with the other water masses.

A schematic presentation of the water masses along a section from Wales southward through the Strait of Anadyr, and the vertical distributions and the T-S relationship at several stations along the section are shown in figure 9 (foldout). The separation of the shaded water-mass types in the schematic diagram represents the boundary between the water masses. In most cases this change is abrupt, but in some cases the change takes place over a fairly broad region of transition as indicated by the wider separation.

The Alaskan Coastal Water is confined to a narrow region very near the coast. The Modified Shelf Water lies along the bottom over most of the section and appears at the surface in the center of the section near the Siberian Coast. At the surface, a moderate sized area of Intermediate Water exists between the Alaskan Coastal Water and the Modified Shelf Water, but at depths the Modified Shelf Water intrudes close to the coast. Intermediate Water passing around the western end of St. Lawrence Island is found near the surface near the southwestern end of the section.

Deep Shelf Water is found on the bottom intruding from the southwest into the Strait of Anadyr west of St. Lawrence Island. This water has approximately the same salinity as the Modified Shelf Water but is colder and is separated from it by a marked thermal boundary. The Deep Shelf Water is found also at stations 32 through 34 on the south side of St. Lawrence Island. It is a persistent type and was found in this region in both investigations conducted by the University of Washington (see NORTHLAND station N-363, fig. 9). Both past and present data indicate that the Deep Shelf Water intrudes from the southwest into the Strait of Anadyr, but during late summer does not extend to the Bering Strait. Thus it appears that although there may be northward movement of water along the bottom in this region, it is so slow that it is warmed several degrees as it rises into the shoaler area north of St. Lawrence Island. In fact, data from earlier sources indicate that this temperature boundary between Deep Shelf Water and Modified Shelf Water recedes southward from the region of Bering Strait as the summer season progresses.

The whole system of water increases in density with distance from the Alaskan Coast, except where the surface flow is interrupted by the barrier created by St. Lawrence Island. From the density distribution and from the direct current observations made in Bering Strait,<sup>5,6</sup> it appears that the water masses are flowing slowly northward throughout the area, converging toward Bering Strait with a rapid flow being concentrated near the coast in the Alaskan Coastal Water and at the boundary between it and the Intermediate Water.

## BERING STRAIT

Bering Strait, some 47 miles in width at its narrowest portion and averaging about 27 fathoms in depth, is the only connection between the waters of the Bering Sea and the Chukchi Sea. A schematic section showing the water masses flowing through the east side of Bering Strait is given in figure 10 (foldout).

Three water masses are found passing through Bering Strait: Alaskan Coastal Water, Intermediate Water, and Modified Shelf Water. The boundaries between the water masses are very sharp, in fact, they are often visible as marked convergence lines at the surface. The geographical position of the convergences exhibited a tendency to shift about a mean position, probably because of changes in wind conditions and variations in the fresh water supply. Secondary convergence lines indicated cellular circulation with the axes parallel to the direction of the currents within the Alaskan Coastal Water.

The Alaskan Coastal Water extends westward on the surface for about 4 to 8 miles from the Cape Prince of Wales. Modified Shelf Water occurs from the surface to the bottom near Little Diomed Island, and, according to University of Washington data, this same phenomenon occurs throughout the western half of the Strait (see NORTHLAND station N-333, fig. 10). On the Alaskan side, the Alaskan Coastal Water intrudes along the bottom close to the coast beneath the Intermediate Water, which occurs only as a narrow separating wedge. Thus, the Deep Shelf Water of the Bering Sea shows no continuity through the Strait. The other three water masses found in the southern approaches, Alaskan Coastal Water, Intermediate Water, and Modified Shelf Water, are continuous through the Strait into the Chukchi Sea. The flow is to the north through the entire width of the Strait, and a concentrated flow exists near the boundary between the Alaskan Coastal Water and Intermediate Water on the eastern side.

In the observations in the published data (limited to summer conditions), on one occasion, in 1933,<sup>17</sup> the current was observed to flow south in Bering Strait. This occurred only very near Cape Deshneva on the Siberian Coast, with a speed of about 30 centimeters per second at the surface and at 15 meters depth, decreasing to about 10 centimeters per second at the bottom. This flow, however, did not continue southward along the coast but was swept northward again by the dominant north-flowing currents.<sup>17</sup> Although this south-flowing current is of slightly lower salinity than the Modified Shelf Water, there is no reason to believe that the over-all water-mass distribution is materially affected by limited and sporadic reversals of current on the extreme western side of the Strait.

## EASTERN CHUKCHI SEA

Distributions of temperature and salinity in the eastern Chukchi Sea for the surface are shown in figure 5, and for 80 feet (approximately 25 meters) in figure 6. Again the presentations for the surface show an average condition for the two series of observations made about two weeks apart during August. A definite increase in the

<sup>17</sup> Chelyuskin Expedition, 1933-1934 *The Voyage of the Chelyuskin, by Members of the Expedition Macmillan, 1935*. Professor Otto J. Schmidt writes in this narrative report: "After making a number of loops [near Cape Serdzekamen] the Chelyuskin took a southeasterly direction and on November 3 we entered Bering Strait. We entered the drifting ice-pack together, but not under our own power. All the same, in one voyage there we were, arrived at Bering Strait. On November 5 we were already half-way through, near St. Diomed Island. . . . Though the distance to clear water was not great (about 20 kilometers), the ice was extremely solid . . . .

" . . . Then suddenly our ice-pack began a rapid northerly drift. It was clear that we were in the course of a powerful current from the Pacific into the Arctic Ocean towards Herald Island . . . ."

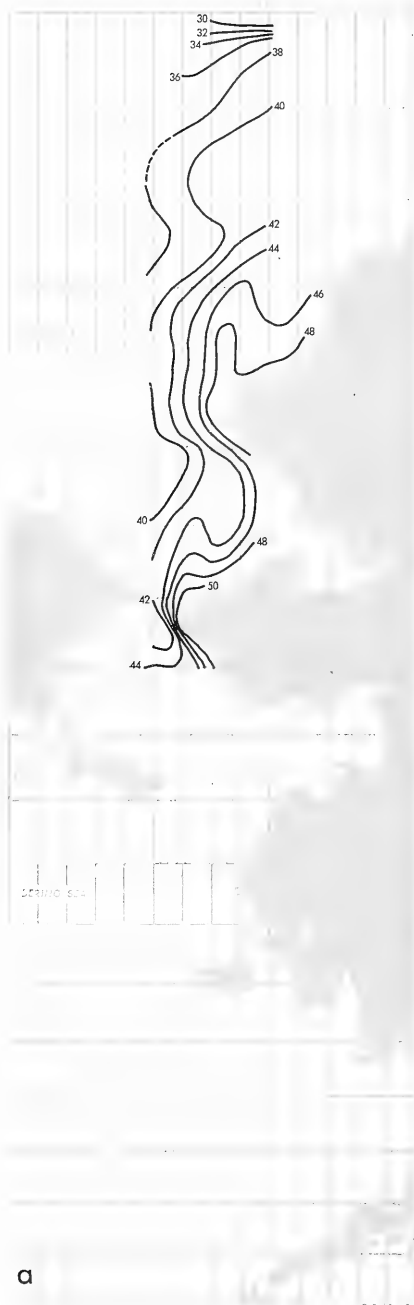


Figure 5. Distributions of (a) surface temperature ( $^{\circ}\text{F}$ ) and (b) surface salinity ( $\text{‰}$ ) in the eastern Chukchi Sea.

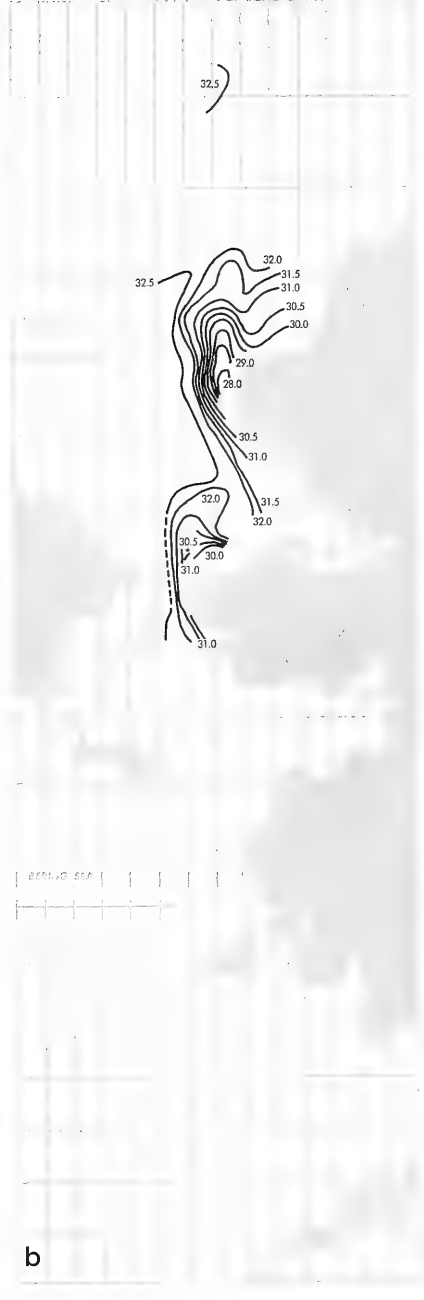
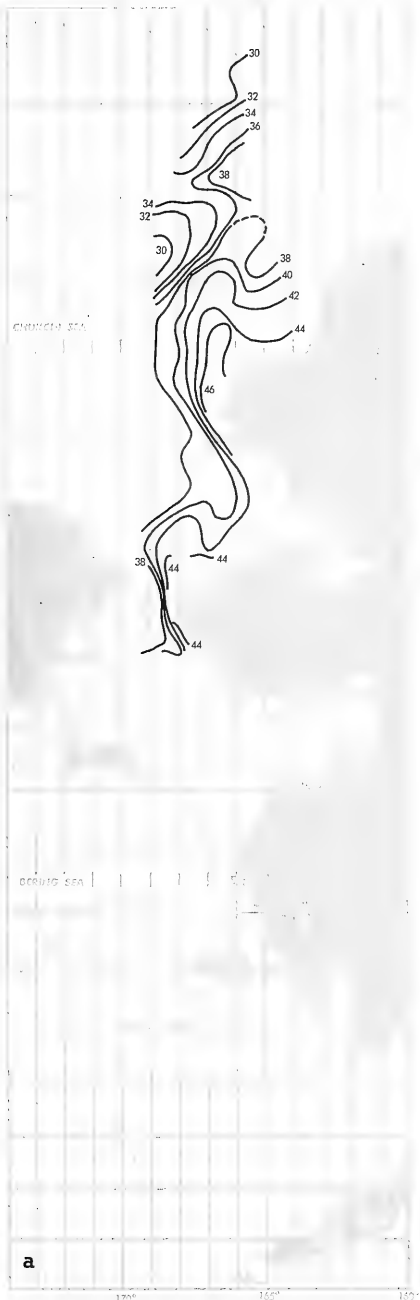


Figure 6. Distributions of (a) temperature ( $^{\circ}\text{F}$ ) and (b) salinity ( $\text{‰}$ ) at 80 feet in the eastern Chukchi Sea.

amount of low-salinity water along the coast, especially north of Pt. Hope, was observed between the two series. Little change was observed at the 80-foot level except a slight salinity decrease very near the coast.

In the Kotzebue Sound region the warmer low-salinity Alaskan Coastal Water can easily be followed flowing around the Sound parallel to and near the coastline. However, as the distance from the shore is increased the temperature and salinity patterns dissociate, a phenomenon not observed in the shallow Bering Sea. The surface temperature west from Kotzebue Sound decreases continuously to the westward while the salinity increases until it reaches a maximum of about  $31.50\text{‰}$  and then decreases sharply to less than  $30.00\text{‰}$ . The latter salinity occurs directly north of the Bering Strait and is caused by the cold Siberian Coastal Water which flows southeastward along the Siberian Coast but is turned northward near East Cape by the strong flow through the Strait. This turning point must fluctuate with the strength of the flow along the Siberian Coast and would account for the rare observations of a southerly current at Cape Deshneva. At the 80-foot level, both the horizontal temperature and salinity gradients are more pronounced than at the surface. The salinity distribution, in particular, shows that the shelf waters persist over the greater part of the shelf at the bottom even in late summer. Thus, large seasonal variations occur only very near the coast and in the surface waters.

Figure 11 (foldout) presents schematically the distribution of the water masses along a section extending from Shishmaref Inlet (C) to the northwest into the central part of Kotzebue Sound (C') and back northeastward to Pt. Hope (C''). Alaskan Coastal Water extends at the surface some 40 miles seaward near Shishmaref Inlet. A large region of Intermediate Water is associated with the maximum salinity in the surface distribution, and the Siberian Coastal Water intrudes as a shallow layer in the western apex of the section. Modified Shelf Water occupies most of the deeper region.

The second part of the section (C' to C'') northeastward to Pt. Hope shows that the Alaskan Coastal Water is concentrated within less than 10 miles of the coast and the zone of the Intermediate Water tends to be narrower than in the first part. Both the Siberian Coastal Water and the Modified Shelf Water water masses intrude much closer to Pt. Hope than to Shishmaref Inlet. It will be recalled that a similar tendency for the Intermediate Water zone to become narrow on the south side of a point of land was observed in the section running southwestward from Cape Prince of Wales (fig. 9).

Figure 12 (foldout) presents schematically the distribution of the water masses along a section northwestward from near Cape Lisburne. The Alaskan Coastal Water occupies an extensive region at the surface. The Intermediate Water is associated with a weak salinity maximum at the surface and beneath it lies Modified Shelf Water. At the seaward limit of the section Modified Ice Melt appears as a shallow surface layer. This location suggests that the boundary of the ice lies southwestward from station 90, although the boundary of the ice may have moved south in the two weeks since the ice was actually reached at station 90.

Figure 13 (foldout) shows the distribution of the water masses from Cape Lisburne northward to  $73^{\circ}\text{N}$  where the ice pack was encountered on this survey. The sections in this figure were taken following a period of high southerly winds, Beaufort force 5 to 7, and while the winds still remained at about force 4. The drift ice had moved northward with the wind and very little ice was encountered prior to reaching the definite boundary of closely packed drift ice into which the wooden-hulled vessel could not penetrate.

The same water masses exist along this section as along the previous one, but to a greater extent. Intermediate Water at the surface is associated with the center of high salinity (31.50 ‰) and a tendency for cyclonic circulation. At this distance from the coast there has occurred less mixing with Alaskan Coastal Water so that the central part of this Intermediate Water region still contains a high percentage of the Modified Shelf Water.

A water mass having the same characteristics as, but not geographically connected with, the Deep Shelf Water of the Bering Sea appears along the bottom at the seaward end of the section. The nomenclature is retained because we believe that the two masses have the same general origin (see discussion in Conclusions).

In the region of the drifting ice along the periphery of the ice pack is cold low-salinity Ice Melt. This water has the same salinity characteristics as the previously defined Modified Ice Melt (fig. 2) and thus is differentiated from it only by temperature, indicating that it warms rapidly as soon as it is isolated from the melting ice pack. On the other hand, the Ice Melt water has the same temperature characteristic as the Deep Shelf Water and is differentiated from that mass only by salinity.

In summary, the three water masses, Alaskan Coastal, Intermediate, and Modified Shelf Waters, are continuous from the Bering Sea through the Chukchi Sea. Deep Shelf Water occurs in both seas but has no continuity through the Strait at this season. The Siberian Coastal Water, Modified Ice Melt, and Ice Melt are found in the Chukchi but not in the eastern Bering Sea.

## surface currents

Movements of the water masses are generally determined by dynamic computations, by direct current observations, or qualitatively by the temperature and salinity distributions.

The dynamic topography of the surface, computed over a selected reference level, indicates the speed and direction of the current at the surface relative to that of the reference level.<sup>18</sup> The relative current was computed over a reference level of 130 feet to determine if this method would agree with the few observed current measurements and thus give a valid picture of the surface-current pattern throughout the area. In most instances, except in Bering Strait where the relative current was large, the computed current was only a small fraction of that observed. It was evident that the movement at the reference level was usually much greater than the relative current computed between the 130-foot level and the surface.

Another means of determining the speed of the current is by the geographic displacement of water of a given type during a limited time. This method was used to determine the speed of the coastal current from Kotzebue Sound around Pt. Hope. Low-salinity water of less than 29 ‰ was found at station 67 on 10 August 1949, 0405Z, but did not appear northward along the coast. Similar low-salinity water was found at station 149 on 22 August 1949, 1735Z. These measurements imply a progress of about 200 miles (a minimum value because of the mixing) along the coast in 12½ days, an average speed of between 0.5 and 0.9 knot depending on the course traveled.

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<sup>18</sup> J. W. Sandstrom and B. Helland-Hansen "Über die Berechnung von Meeresströmungen" *Norwegian Fishery and Marine Investigations*, vol. 2, no. 4, 1903.

The general pattern of the surface currents can be inferred from the distribution of the water masses taken together with the dynamic topography and direct current measurements. The currents obtained in this manner are shown in figure 7 for the north-eastern Bering Sea and eastern Chukchi Sea during the late summer of 1949.

The flow is predominantly northward from the region between St. Matthew and St. Lawrence Islands to as far north as  $70^{\circ}$  N. The flow of the Alaskan Coastal Water close to the coast is very pronounced. In the Bering Sea, the current passing around the east end of St. Lawrence Island and north to Bering Strait is somewhat strengthened by outflow from Norton Sound and the Yukon River. The major current through Bering Strait appears in the eastern half of the strait.

In the Chukchi Sea, in addition to the coastal current a moderate flow entering from the southwest appears along the northern side of the tongue of Siberian Coastal Water. This flow probably contributes to the split in current occurring west of Pt. Hope and Cape Lisburne. In this region one branch of the split current appears to proceed northwest toward Herald Shoal and the other follows northeast along the Alaskan Coast. North of  $70^{\circ}$  N, the predominant feature in the area surveyed is the eddy between the coastal current and the Arctic drift with an indication of a weak south-westward return of lower-salinity surface water in the northwestern part of the area.

## conclusions

In the preceding sections the identification, distribution, and movements of the water masses have been discussed with only slight reference made to their origin. From the present available data, an hypothesis of development of the system is proposed for consideration and further investigation.

During the winter months the ice boundary progresses southward, not by current drift or wind effect but because of the atmospheric cooling. Because of the high winds, lack of run-off, and the freezing of the ice, a vertically uniform water mass probably exists in late winter from the Chukchi Sea through Bering Strait and over the greater part of the shallow Bering Sea. This water mass is then in equilibrium with the freezing ice, which for water of salinity of  $33.00 \text{ }^{\circ}/_{00}$  is a temperature of  $28.8^{\circ}$  F.\* This is the origin of the Deep Shelf Water.

As the ice recedes in the spring, the winds continue mixing so that Ice Melt water is dissipated except at the immediate ice boundary. However, the effects of surface heating and solar radiation as spring progresses warm the surface layers of the water mass, developing the Modified Shelf Water.

At the same time the warmer coastal drainage progressively creates the Alaskan Coastal Water near shore. The outflow from several rivers renews the water mass downstream so that the identity or characteristics are maintained at least as far northward along the Alaskan Coast as Cape Lisburne. The stations northeast of Cape Lisburne indicated some deterioration of the Alaskan Coastal Water.

The Intermediate Water appears to be largely a broad zone of mixing which develops between the Modified Shelf Water and the Coastal Water. It first occurs south of St. Lawrence Island off Cape Romanzof where it extends over a wide area,

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\* An expedition aboard the USS BURTON ISLAND (AGB-1) in February 1951 observed vertically uniform conditions in the region of the ice in the northeastern Bering Sea northward to the latitude of  $64^{\circ} 50'$ . Observed temperature was  $28.9^{\circ}$  F and salinity ranged from  $31.8 \text{ }^{\circ}/_{00}$  to  $33.4 \text{ }^{\circ}/_{00}$  depending upon location.

homogeneous from top to bottom. It may have its origin in mechanical mixing over the bottom rise in that area. It further appears to be renewed by mixing between Alaskan Coastal Water and Modified Shelf Water.

In the Chukchi Sea region it would be anticipated that the run-off of the rivers along the north Siberian coast would create a coastal current moving southward along the western side of Bering Strait as a counterpart to the northward flow of Alaskan Coastal Water. Such a current was not found in the Bering Strait, nor was it indicated by the observations of USCGC CHELAN in 1934<sup>5</sup> or the NORTH-LAND in 1937 or 1938.<sup>6</sup> Thus, it appears that the low-salinity cool water found directly north of Bering Strait to the west of Kotzebue Sound is the Siberian coastal current which has been diverted by the strong flow through Bering Strait and is carried northeastward away from the coast. This mass of Siberian Coastal Water, which moves out of the surveyed area, with time and displacement would tend to lose its identity because of mixing. The Modified Ice Melt water also moves west and southwest out of the area surveyed. It is possible that some of this water moves southward in the region of Wrangel Island and combines with the flow of Siberian Coastal Water to set up a weak cyclonic gyral between Wrangel Island, the Siberian Coast, and the region near Herald Shoal.

The shallow Bering and Chukchi Seas thus form a coastal system with a general structure which is consistent from year to year. The water masses are derived from four distinct sources, Alaskan coastal drainage, Siberian coastal drainage, freezing of the ice in winter, and melting of the ice in summer. The other water masses are modifications of these, two arising from heating effects and the third from a mixing between water masses.



Figure 7. Surface currents in the eastern Bering Sea and the eastern Chukchi Sea. Surface current arrows indicate only approximate strength and persistency of current.

## recommendations

Our knowledge of the American waters of the Bering Sea, Chukchi Sea, and Arctic regions has been increasing at a relatively rapid pace since 1947. Subsequent to the presently reported cruise, unpublished oceanographic surveys have been carried out in the navigable regions of the Beaufort Sea in conjunction with BAREX Operations of 1950, 1951 and 1952. SKIJUMP Operations<sup>19,20</sup> have furnished spot data on oceanographic conditions under the icepack, and a major effort is being applied in extending the boundaries of the surveyed areas. There still remain, however, several problems in the Bering and Chukchi Sea regions for which more data would be desirable.

Observational data are needed in these areas at other seasons of the year to supplement the summer data and the sparse amount of winter data. Such information, including year-around current measurements at Bering Strait, would assist in answering the long-standing question of the driving force behind the persistent northerly flow through Bering Strait in summer. Although it has been generally assumed that there is a difference in level between the Pacific and Arctic Oceans<sup>8</sup> which results in the northerly current year around, this theory has not been satisfactorily substantiated. It is possible, however, that a change in level may take place locally within the Bering and Chukchi Seas due primarily to the difference between wind stress exerted in the summer and in the winter, and secondarily to the run-off of fresh water from the western Alaskan Coast during the summer months. (Unpublished data at NEL on currents in the eastern side of the Bering Strait indicate that even in summer months the current through the Strait can be reversed by several days of strong northerly winds.)

The mechanism which results in the large area of nearly homogeneous water in the Nunivak Island, St. Matthew Island, Cape Romanzof area is still unknown, as are the relative amounts of water supplied to the region by flow from the southwest across the deep Bering Sea and by flow from the south through the eastern Aleutian passes.

Present data on the circulation around St. Lawrence Island which forms a partial block to Bering Strait are somewhat contradictory, particularly regarding structure to the north of the island. The main body of data supports the existence of a warm region centered north of the island, while other data indicate an area of cold high-salinity upwelling. A knowledge of the seasonal development of the water structure in this area and its relation to the local wind conditions might resolve this apparent conflict.

Lastly, a gap exists in the data along the Alaskan Coast between Cape Lisburne and Pt. Barrow. Although this region appears to have a simple coastal circulation, a study of this area would be of value to tie in the Chukchi Sea work with that done in the Beaufort Sea.

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<sup>19</sup> J. F. Holmes and L. V. Worthington *Project SKIJUMP Conducted during the Period February-May 1951* (Woods Hole Oceanographic Institution, Reference no. 51-67) September 1951.

<sup>20</sup> J. F. Holmes and L. V. Worthington *Oceanographic Studies on Project SKIJUMP II* (Woods Hole Oceanographic Institution, Reference no. 53-23) April 1953.





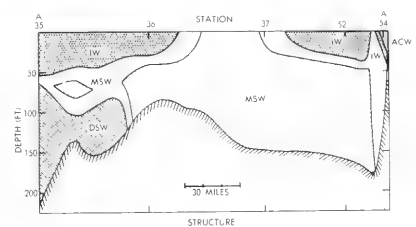
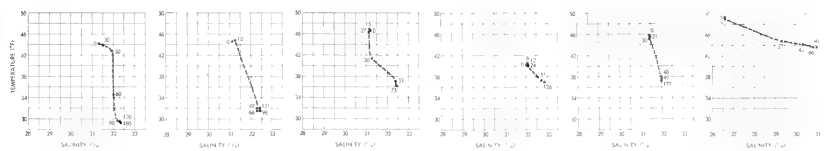
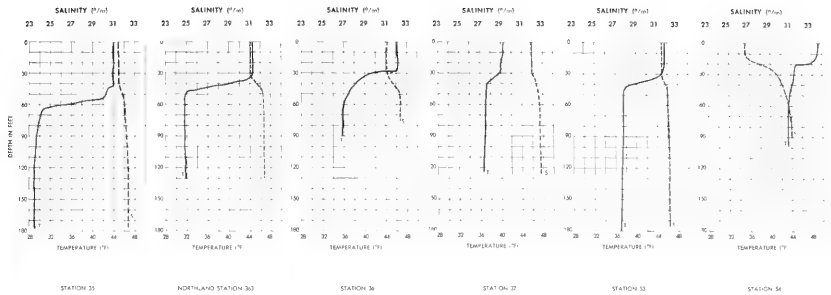
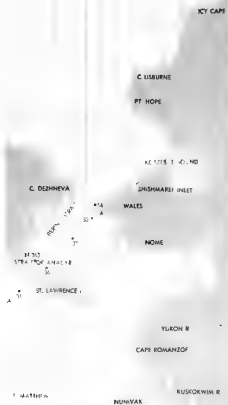


Figure 9 Water mass structure along a section from Wales to Strait of Andoy with vertical temperature and salinity distributions and TS relationships for selected stations



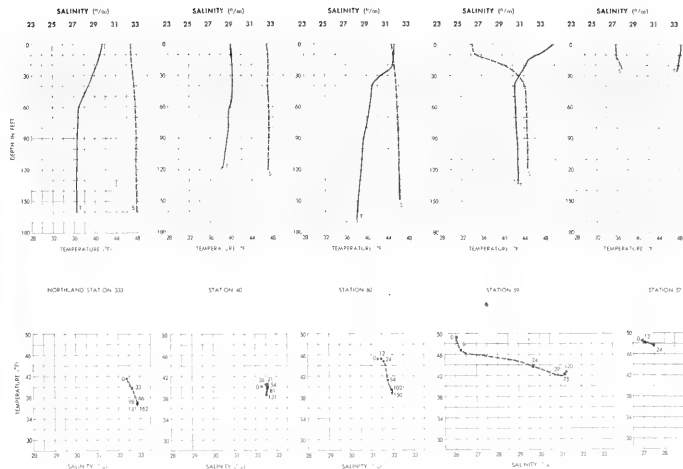
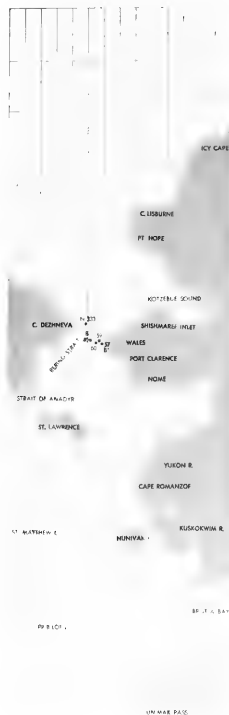
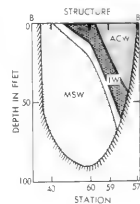


Figure 10 Water-mass structure in eastern Bering Strait with vertical temperature and salinity distributions and T-S relationships for selected stations.





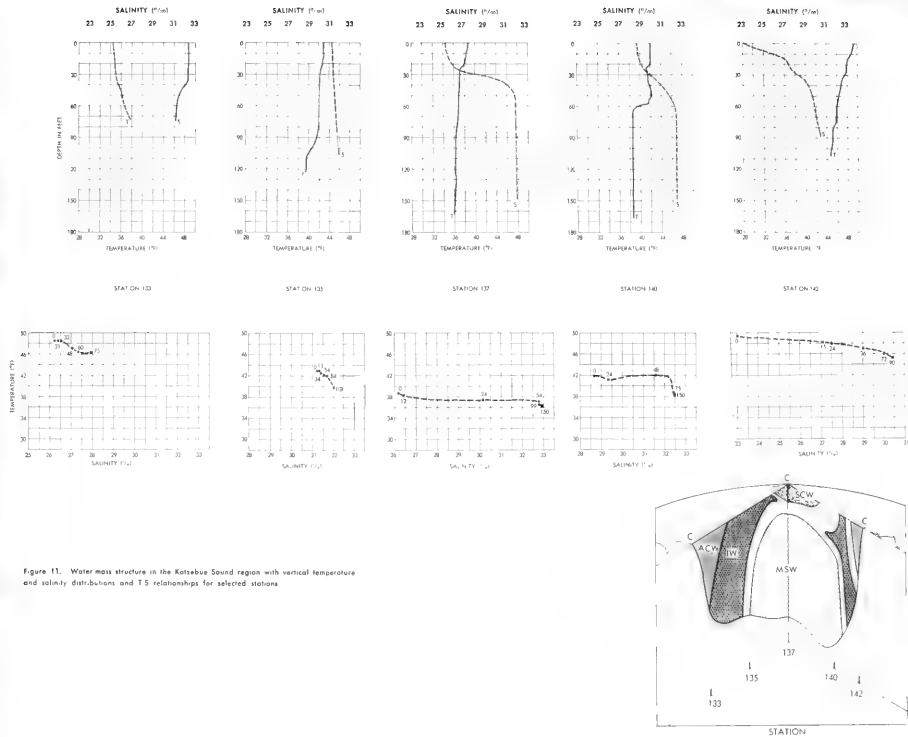


Figure 11. Water mass structure in the Kotsabue Sound region with vertical temperature and salinity distributions and TS relationships for selected stations



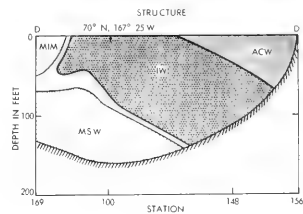
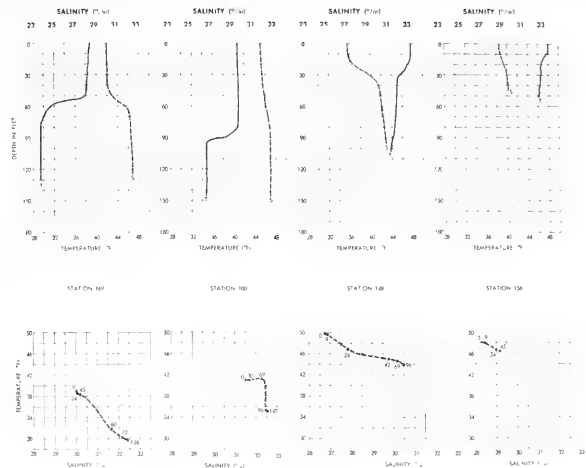
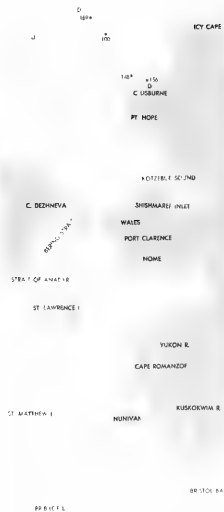


Figure 12 Water-mass structure along a section northwestward from Cape Lisburne with vertical temperature and salinity distributions and T-S relationships for selected stations



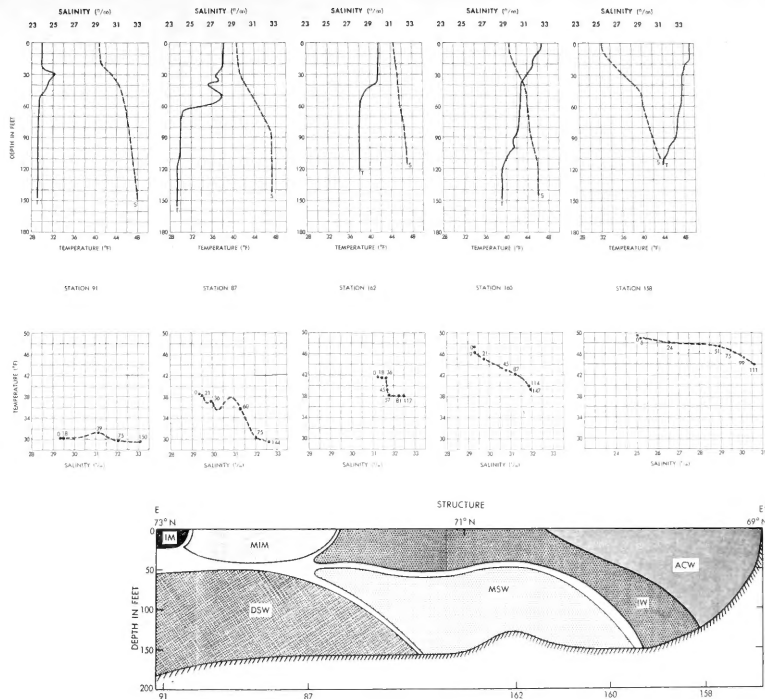


Figure 13. Water-mass structure northward from Cape Lisburne to the ice pack with vertical temperature and salinity distributions and T-S relationships for selected stations



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During a two-month cruise in the summer of 1949, systematic measurements of the physical oceanography of the shallow eastern Bering and Chukchi Seas and of the Bering Strait were made. The temperature, salinity and density of the water were established, and the distribution, movements, and interaction of the water masses present in the area were investigated. A description of the results of these studies is presented.

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2. Oceanography — Chukchi Sea
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- II. Tully, J. P.
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